FINAL TECHNICAL REPORT

AWARD# G15AC00079

TITLE: THEODOLITE SURVEY MONITORING OF FAULT CREEP ON SAN FRANCISCO BAY REGION FAULTS (2016-2020)

Principal Investigators / Authors:

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NON-TECHNICAL ABSTRACT

We report on the results of the field surveys conducted during 2016-2020 for determining the rate of aseismic fault movements (i.e., creep) at a total of 88 sites along a dozen different active earthquake faults in the San Francisco Bay region; 20 of the 88 sites were established within the most recent 5-year grant period. We continue to build on a 40-year creep monitoring program that has been supported by the USGS—Earthquake Hazards Program (EHP) since its initiation. Our creep monitoring surveys document the character and rates of long-term creep on Bay Region faults. By establishing long-term behavior of creeping faults in the Bay Region, the database provides a critical foundation of knowledge for recognizing anomalous creep movements that would potentially be useful indicators of forthcoming earthquakes. The database augments other types of data collected for the purposes of monitoring the contemporary behavior of earthquake faults in the Bay Region. Knowledge of the behavior of creeping faults provides basic input for understanding how the earth's crust deforms in response to the build up and release of tectonic stresses, and it therefore provides information that is directly relevant to earthquake hazard assessment in the greater San Franciscan Bay Region.

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TECHNICAL ABSTRACT

During the 2016-2020 funding cycle of the USGS Earthquake Hazards Program (EHP) the San Francisco State University creep monitoring project continued to collect and analyze near-field geodetic strain (creep) data using high-precision theodolite surveys of alinement arrays along strike-slip faults in the heavily populated and seismically active San Francisco Bay Region of northern California. The data establish baseline characteristics of aseismic creep to which future survey data can be compared, thus offering prospects for identifying anomalous fault behavior that may be precursory in nature to imminent damaging earthquakes in the highly populated SF Bay region. The baseline creep data also provide the basis for estimating variations in fault locking depths which in turn inform earthquake source models and seismic hazard assessments for the region (Lienkamper et al., 2014).

Since inheriting the project in 2001we have critically analyzed our data in consultation with a number of researchers at the USGS in an effort to improve our data coverage and data quality. Of particular significance to test the proposal by Funning et al. (2007), based on InSAR that the northern Rodgers Creek fault may creep as much as 6 mm/yr, comparable to the Hayward fault. Both new sites exhibited large dextral creep events in a 2009 survey, thus apparently supporting the idea that significant creep does occur on the Rodgers Creek fault. This section of the fault was modeled as fully locked in the WG03 earthquake forecast. Significant creep events have already been observed in many of these other new sites on fault segments that previously had no data.

Our results continue to delineate the amount of movement across a width of about 55-280 m at ~80 sites along San Francisco Bay Region faults. The fault width over which we survey is not easily covered by other monitoring methods or measuring instruments. For some faults or fault segments, our measurements continue to provide the only information on present creep rates and, by implication, the minimum contemporary slip rate, which is the predominent earthquake source parameter that drives seismic hazard assessments.

We maintain a SFSU Creep Monitoring Project web site (http://funnel.sfsu.edu/creep/) that describes the project, project objectives, personnel, creep characteristics and measurement, map of creep measurement sites, and creep site table with data plots and site descriptions. The web site has direct links to annually updated project data recorded from 1979-present and links to our most recent on-line reports (e.g., McFarland et al., 2018), thus making our results and data accessible to anyone in the scientific community and to the general public. An objective for the first year of the next funding cycle is to coordinate with fellow geodetic researchers in the region to provide an online format for the public to access integrated maps showing our collective geodetic networks, with direct access to all geodetic data bases. This proposed collaboration will seek to link the geodetic projects data and results through a link with USGS Earthquake Hazards Program.

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INTRODUCTION

The primary purpose of the research we conducted in 2016-2020 was to build on our decades-long database for characterizing variations in creep behavior on Bay region faults. Earlier data (1979-2001) were reported in Galehouse (2002) and were analyzed and described in detail in a summary report (Galehouse and Lienkaemper, 2003). A complete analysis results obtained on the Hayward Fault prior to and following the Loma Prieta earthquake was presented in Lienkaemper et al. (2001). Hayward fault creep behavior was updated in report by Lienkaemper et al. (2012). Lienkaemper et al. (2014a) provide a new overview and analysis of fault creep along all sections of the northern San Andreas Fault system, from which they estimate by how much fault creep reduces the seismic hazard for each fault section.

From 1979 until his retirement from the project in 2001, Jon Galehouse of San Francisco State University (SFSU) and many student research assistants measured creep (aseismic slip) rates on these faults. The creep measurement project, which was initiated by Galehouse, continued through the Geosciences Department at SFSU from 2001-2006 under the direction of Karen Grove and John Caskey (Grove and Caskey, 2005) and since 2006 under Caskey (2007). Forrest McFarland manages many of the technical and logistical project operations, as well as data processing and compilation. Data from 2001-2007 are found in McFarland and others (2007). In 2009, we began releasing annual updates of the full history of raw survey data (1979-present) through a permanent publication link (OF2009-1119), while publishing more detailed analyses of these data in the scientific literature, such as Lienkaemper et al. (2014a). We maintain a project Web site (http://funnel.sfsu.edu/creep/) that includes the following information: project description, project personnel, creep characteristics and measurement, map of creep-measurement sites, creep-measurement site information, and links to data plots for each measurement site. Our most current, annually updated results are, therefore, accessible to the scientific community and to the general public. Information about the project can currently be requested by the public by an email link (fltcreep@sfsu.edu) found on our project Web site.

METHODS

Measurement Method: The measurement method used in this investigation is a relatively simple triangulation method. The theodolite or total station instrument is centered and leveled over a fixed point on one side of the faults and designated as the “instrument station” (IS), which is a nail pounded into asphalt, a monument that has been installed by project personnel, or a previously-existing below-grade city monument that is fortuitously located. Traverse targets are set up over an “orientation station” (OS) on the same side of the fault as the IS and over an “end station” (ES) on the opposite side of the fault. These stations are emplaced such that a line from the IS to the ES is as perpendicular to the local trend of the fault as is logistically possible. The measured slip needs to be corrected by less than one percent if the line is within five degrees from the perpendicular and by less than two percent if ten degrees from the perpendicular.

The IS and ES are far enough apart so that both stations are likely to be out of the main zone of fault slip, yet close enough together so that accurate readings can be made. The IS to ES distance is accurately determined at each site by using at least two of three different methods. First, the distance can be measured carefully using a surveyor's tape to confirm mathematical methods. Second, an angle between an IS and ES can be measured using the theodolite on the total station, the IS to ES distance can be taped to the nearest mm, and then the IS to ES distance can be calculated trigonometrically. Third, the distance can be measured using an electronic distance measuring (EDM) instrument that is part of the total station.

The OS to IS to ES angle is determined to the nearest tenth of a second using a slight modification of the measurement method that was described in detail in technical reports submitted to the USGS by J. Galehouse. The present method involves measuring the angle eight times on each measurement day, and then using the mean value.

<u>Precision of Measurements:</u> The precision of slip determinations depends on a number of factors. The instruments must be of high quality. From 1979-2002 our surveys employed a Wild-Heerbrugg Model T3 Precision (0.5 sec) Theodolite (analogue instrument) that was purchased with USGS funds at the initiation of the SFSU creep monitoring program. We now employ a digital Wild-Heerbrugg Model T2002 Precision (0.5 sec) Theodolite that was donated by to the SFSU Geosciences Department by Caltrans in 2002. The digital T2002 Theodolite improved on what was already an excellent first-order system for triangulation surveying. We have continued to use traverse targets made by Lietz and Wild, which are of excellent quality. All of these instruments are equipped with optical plummets that facilitate centering the instruments precisely over the station points. The total station is self-leveling, provides digital data sets, improves on data collection efficiency, and may improve precision.

In addition to instrument quality, precision also depends on the care and skill of the person(s) making the measurements. We have continued to use San Francisco State University undergraduate geology majors as research assistants and to keep a close check on the precision of all instrument operators by monitoring angle closure values and ranges. Some range in angle measurement is to be expected and may be primarily due to slight eccentricities in the optical plummets of the theodolite and the traverse targets. It is for this reason that the instruments are rotated 180˚ after four angle measurements. Some of the range in angle measurements, however, may be due to a human factor. The care and accuracy with which the instrument person centers and levels the theodolite over the IS and the target operator centers and levels the traverse targets over the ES and OS are extremely important. For the more than 3000 site measurements made since 1979, the mean range in the value of the angles determined during each measurement set is about ±3 seconds. There is little difference in the precision of any of the present instrument operators. The average range of about ±3 seconds for the angle measurements in a set gives a standard deviation of about ±2.5 seconds for the mean value. This corresponds to about ±1.2 mm for a 100 m IS to ES distance and about ±2.4 mm for a 200 m distance. This assessment of the precision of the mean angle suggests that slip calculated at one mm or two between successive measurements, whether it is right-lateral or left-lateral, may not be real but may simply be due to the precision limits of the measurement method. As measurements continue to be taken, however, trends in the nature of movement are discerned and average rates of movement can be calculated with a greater degree of confidence in the results. Most of the overall average (mean) values shown on Figures 3 through 7 are ±0.1 mm. With the updated total station instrument this demonstrated high precision has undoubtedly improved because readings can be made more rapidly, thus reducing instrument drift, and digital recording reduces possible operator recording errors. It is also increasingly easy to double check site factors that are used in data calculations.

Accuracy of Measurements: Although the theodolite / total station measurement method can determine changes in the angle between stations at a site quite precisely, an additional concern is whether the measurement results give an accurate determination of the actual fault movement that is occurring at the surface. Of course, the results will reflect less than the total amount of movement along a fault if the zone of movement is wider than the IS to ES distance. This is an inherent aspect of the theodolite / total station method but it is probably not a significant factor at most of the measurement sites; it is certainly much less than for the creepmeter method. However, the results at a particular site must be considered the minimum amount of horizontal movement that is occurring at that general location.

Accuracy errors could arise if one or more of the nails or monuments representing the various stations is moving or has moved systematically or erratically due to nontectonic causes (e.g., traffic, vandalism, subsidence, plant roots). Stations that show signs of having been disturbed are replaced. More potentially serious problems, however, can occur if any of the three triangulation stations moves in response to changes in temperature or rainfall or moves in a downslope direction under the influence of gravity (mass movement creep as opposed to tectonic creep) without any obvious signs of disturbance. Sites have been located in low-relief areas when it is possible to do so. As measurements are continued, we are beginning to detect seasonal changes due to weather and to evaluate the amount of creep that is due to mass movements. See further discussion of error below and in Galehouse and Lienkaemper (2003).

RESULTS

During the 2016-2020 funding cycle of the USGS Earthquake Hazards Program (EHP) we continued our efforts to collect and analyze near-field geodetic strain (creep) data from high-precision theodolite surveys of alinement arrays along strike-slip faults in the heavily populated and seismically active San Francisco Bay Region of northern California. Since 2010, we have decreased the frequency of surveys at most individual sites to about once annually, however the size of our network has nearly doubled in the past decade to over 80 survey sites. (Tables 1a, 1b, and 2; Figures 1, and 2). We now survey ten sites on the Rodgers Creek- Maacama Fault system, seventeen sites on the Concord-Green Valley-Berryessa–Hunting Creek–Bartlett Springs Fault system, and five sites on the West Napa fault rupture that accompannied the Aug 24, 2014 South Napa earthquake (Lienkaemper et al., 2014b; Hudnut et al., 2014; and Brocher et al., 2015). We now monitor for creep at five sites on the Greenville fault where creep has recently been recognized along the northern third of the fault (Lienkaemper et al., 2013).

Table 1 shows the least squares average rate of movement at each site, determined using linear regression, and the simple average rate, determined by dividing the total net right-lateral displacement by the total time measured. For three sites on the Calaveras fault (CV7S, CVWR, CVCR) we calculated average creep using multiple linear regression (MLR) to eliminate accelerated or retarded creep that is associated with large ($M \geq 5.5$) local earthquakes. All measurement sites span a fault width of 57-289 m, except Sites GVRT and SGPR, which span a greater width because of site considerations. The fault width spanned is noted (under "Length" column in Tables 1a, 1b, and 2 and represents the distance from the theodolite on one side of a fault (IS, instrument station; Fig. 1 inset) to a target on the other side (ES, end station). Angles are measured with respect to another target (OS, orientation station). All Hayward Fault sites are summarized in Table 2.

Each data sheet is identified in the upper left by site code and name. Hayward Fault sites are ordered from northwest to southeast using kilometer distances along the fault measured southward from Point Pinole (Figure 2) using the grid in Lienkaemper (2006). Data sheets for all sites are available in the data folder in Excel format to facilitate analysis of the data at http://pubs.usgs.gov/of/2009/1119/ (SFBayRegion.xls and HaywardFault.xls). The raw data are also available as comma-delimited files (.csv). Data for the reporting period 2007-present include the average angle and its 1-σ uncertainty. Also provided for each reading is the current site correction used; the sine of the angular difference between the fault azimuth and azimuth of the array (IS-ES). Each measurement of apparent slip must be divided by its site correction. The data include 88 active measurement sites, including 32 on the Hayward Fault. For all sites with at least three years of surveys, we show summary plots of the creep data by fault zone for the Calaveras and Greenville faults (Figs. 3 and 4), Concord, Green Valley and Bartlett Springs Faults (Figs. 5a and 5b), Rodgers Creek and Maacama faults (Fig. 6), San Andreas and San Gregorio faults (Fig. 7), Hayward Fault (Figs. 8 and 9) and West Napa Fault (Fig. 10).

DATA DISSEMINATION

In 2009, we began releasing the raw survey data annually (1979-present) using this report (OF2009-1119) as a permanent publication link, while publishing more detailed analyses of these data in the scientific literature, such as Lienkaemper et al. (2014a). We maintain a project Web site (http://funnel.sfsu.edu/creep/) that includes the following information: project description, project personnel, creep characteristics and measurement, map of creep-measurement sites, creep-measurement site information, and links to data plots for each measurement site. Our most current, annually updated results are, therefore, accessible to the scientific community and to the general public. Information about the project can currently be requested by the public by an email link (fltcreep@sfsu.edu) found on our project Web site.

CONCLUSIONS

The ongoing goal of our investigation is to build on our decades-long database for characterizing variations in creep behavior on Bay region faults. The results of our work continue to complement recent and ongoing USGS-sponsored studies on regional seismicity by Reasenberg and Simpson (1992, 1997), Hayward fault-slip history (Lienkaemper and Galehouse, 1997; Lienkaemper et al., 2001), static stress changes (Simpson et al., 2001), crustal strain (Prescott et al., 2001; Murray et al., 2006; Bürgmann et al., 1998, 2000; and Funning et al., 2007), and creepmeter emplacement on the Hayward fault (Bilham et al., 2004). The behavior of creeping faults also provides fundamental input for understanding contemporary crustal deformation models and informs models of locked fractions of faults and stress loading rates, and hence source parameters directly relevant to seismic hazard assessment (Lienkaemper et al., 2012, 2013, in press).

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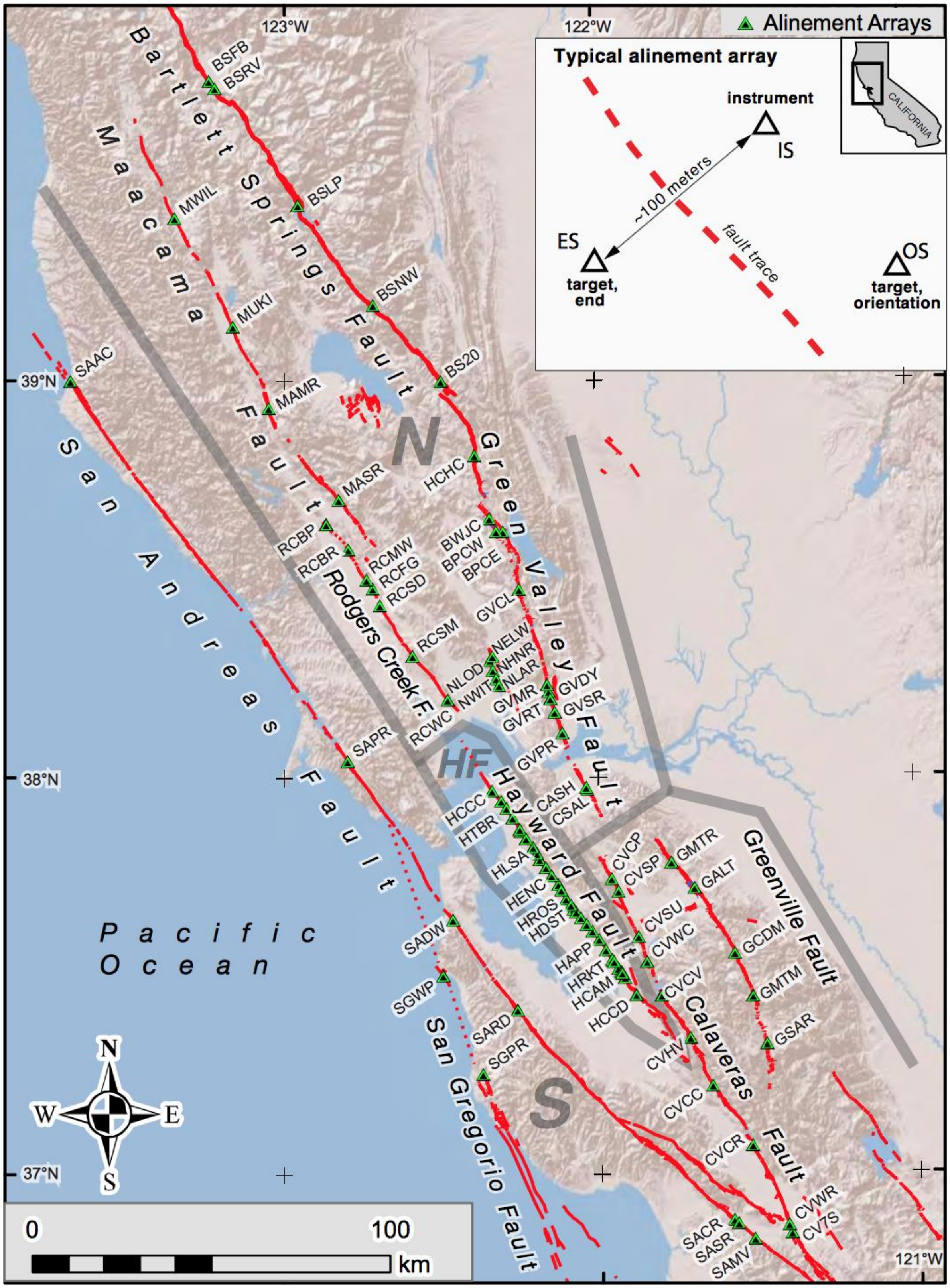

Figure 1. Locations of alinement arrays, San Francisco Bay region. Arrays shown as triangles Summary information for most arrays in table 1. All Hayward Fault arrays in fig. 1 and table 2. Inset is idealized array described in text. Active faults in red (USGS and CGS, 2006); Green Valley Fault (Lienkaemper, 2012); Bartlett Springs Fault (Lienkaemper, 2010); Greenville Fault (Lienkaemper, 2014, unpublished mapping); W. Napa fault, 2014 rupture (Brocher et al., 2015). Regions (gray boundaries labeled HF, N, S) indicate contents of three data file sets: Hayward Fault and San Francisco Bay Region, north and south, respectively.

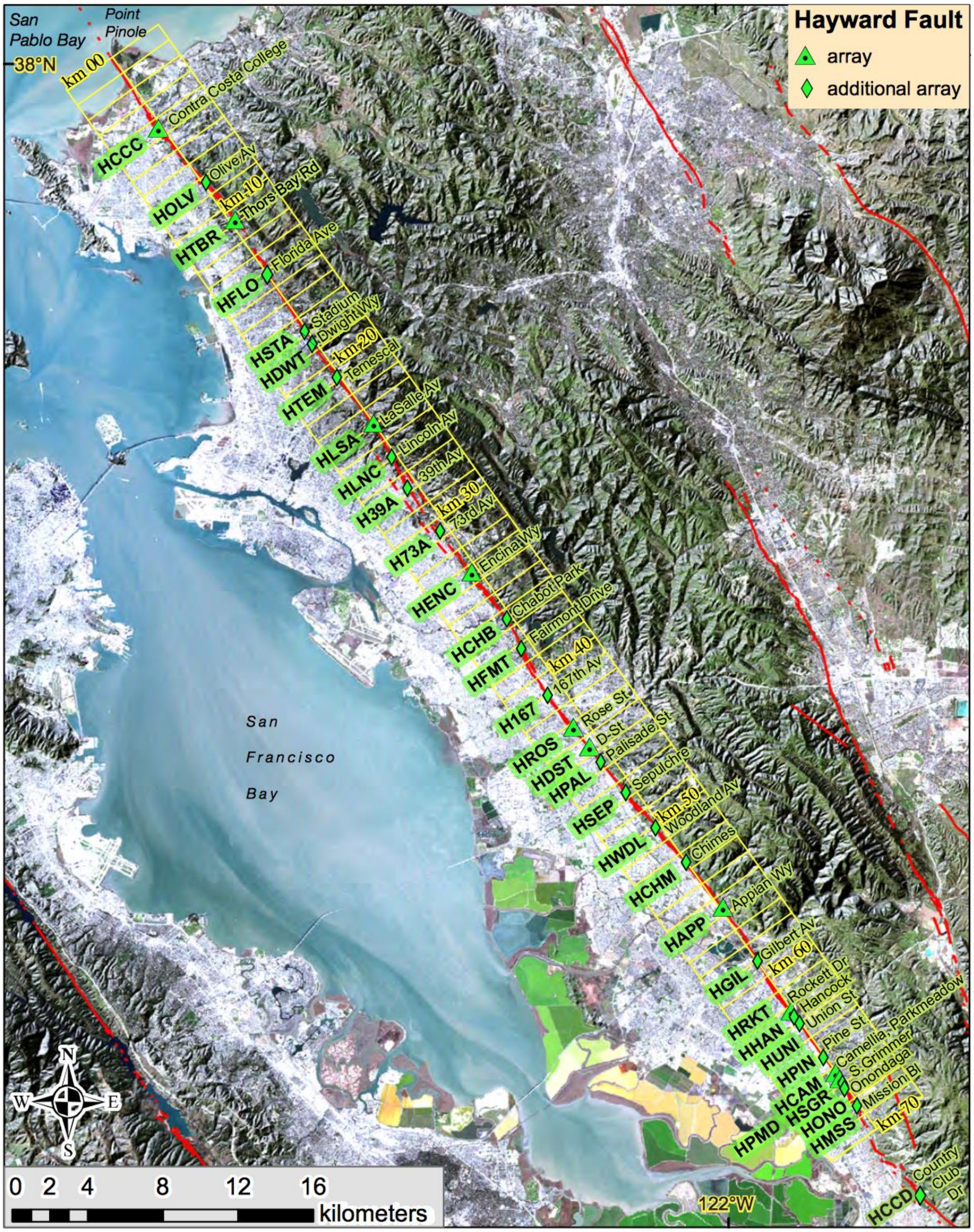

Figure 2. Locations of alinement arrays across Hayward Fault. Includes formerly frequent SFSU sites (triangles) and former annual sites (diamonds), see tables 1 and 2 for additional information. Yellow grid shows distance in kilometers from San Pablo Bay after Lienkaemper (2006). Faults in red zoned as active (Bryant and Hart, 2007).

Table 1a. Average Rates of Right-Lateral Movement, San Francisco Bay Region (Southern data set, region **S**, Fig. 1)

Site Code	Fault	Site Name	Longitude (WGS84)	Latitude (WGS84)	Length (m)	Linear regression average creep rate (mm/yr)	± (mm/yr)	Ave.* creep rate (mm/yr)	yr[2]	
CV7S	Calaveras	Seventh Street	-121.40631	36.84952	89.656	7.7	0.09	7.4	36.1	MLR rate; 1989 step
CVWR	Calaveras	Wright Rd	-121.41381	36.86982	108.700	10.0	0.1	10.1	36.0	MLR rate; 1989 step
CVCR	Calaveras	Coyote Ranch	-121.52521	37.06981	89.431	10.2	0.2	14.8	46.0	MLR rate; '79, '84 eqk. steps
CVCC	Calaveras	Carlin Canyon	-121.64941	37.22206	158.199	7.9	0.3	7.7	5.6	
CVHV	Calaveras	Halls Valley	-121.71616	37.34233	167.404	0.4	1.4	-0.8	5.1	Missed trace: abandoned 2015
CVCV	Calaveras	Calaveras Valley	-121.80616	37.45050	146.650	3.7	0.7	3.8	3.0	Replaces Marsh Road Site
CVWC	Calaveras, Northern	Welch Creek Rd	-121.85183	37.53570	158.534	4.3	0.1	4.2	18.3	
CVSU	Calaveras, Northern	Sunol	-121.87693	37.59850	243.224	2.4	0.3	1.9	12.7	
CVSP	Calaveras, Northern	Shannon Park	-121.93713	37.70649	144.730	1.4	0.2	0.9	13.9	
CVCP	Calaveras, Northern	Corey Place	-121.96083	37.74569	111.204	1.8	0.1	1.2	34.9	
GSAR	Greenville	San Antonio Rd.	-121.47562	37.32678	99.315	—	—	-1.4	1.2	New site 2014
GMTM	Greenville	Mount Mocho	-121.51785	37.44750	70.811	—	—	-2.4	1.6	Installed late 2013
GCDM	Greenville	Cedar Mt. (Mines Rd.)	-121.57385	37.55581	86.641	—	—	-4.0	1.3	New site 2014
GALT	Greenville	Altamont Pass Road	-121.69817	37.72060	88.408	0.7	0.3	0.7	6.2	
GMTR	Greenville	Morgan Territory Rd.	-121.77063	37.78659	102.689	—	—	12.2	1.3	New site 2014
SAMV	San Andreas	Mission Vineyard Rd	-121.52171	36.83502	134.663	11.7	0.1	12.0	25.4	
SASR	San Andreas	Searle Rd	-121.57280	36.87453	262.687	0.9	0.2	-0.3	13.2	
SACR	San Andreas	Cannon Road	-121.58611	36.88261	88	0.1	0.1	0.2	8.2	Abandoned 1998
SARD	San Andreas	Roberta Dr	-122.26154	37.41700	91.176	0.5	0.04	0.4	25.3	
SADW	San Andreas	Duhallow Way	-122.46564	37.64419	205.637[1]	-0.2	0.02	0.0	35.0	
SAPR	San Andreas	Point Reyes	-122.79796	38.04398	70.880	-0.05	0.03	0.1	30.4	
SAAC	San Andreas	Alder Creek	-123.69059	38.99986	265.982	0.4	0.04	0.5	34.6	
SGPR	San Gregorio	Pescadero Rd	-122.37294	37.25450	454.945[1]	0.9	0.06	0.6	33.2	
SGWP	San Gregorio, Seal Cove	West Point Ave	-122.49664	37.50369	262.033	-0.12	0.04	0.2	35.7	

*Average = total slip/total time
[1]Combined ESE and ESW lengths
[2]Number of years of observation

Table 1b. Average Rates of Right-Lateral Movement, San Francisco Bay Region (Northern data set, region **N**, Fig. 1)

Site Code	Fault	Site Name	Longitude (WGS84)	Latitude (WGS84)	Length (m)	Linear regression average creep rate (mm/yr)	± (mm/yr)	Ave.* creep rate (mm/yr)	yr[2]	
BPCE	Berryessa	Pope Canyon, East trace	-122.29829	38.62156	99.040	-0.4	0.7	0.0	4.6	
BPCW	Berryessa	Pope Canyon West trace	-122.32086	38.62179	76.096	-1.8	0.8	-1.5	4.6	
BWJC	Berryessa	Jerd Creek, West trace	-122.34194	38.65523	86.598	1.4	0.6	1.5	3.1	
BS20	Bartlett Springs	Highway 20	-122.49721	39.00138	163.948	1.0	0.4	1.1	5.9	
BSNW	Bartlett Springs	Newman Springs	-122.71436	39.19380	141.000	—	—	-0.7	1.9	OS replaced, read 2015
BSLP	Bartlett Springs	Lake Pillsbury	-122.95726	39.44560	102.186	3.2	0.1	3.0	10.0	
BSRV	Bartlett Springs	Round Valley	-123.22755	39.74003	184.164	0.4	1.5	0.6	3.0	Destroyed
BSFB	Bartlett Springs	Fairbanks Road	-123.24823	39.75875	101.345	-0.2	0.2	-0.3	5.2	Not read 2015
CASH	Concord	Ashbury Drive	-122.03524	37.97189	133.189	3.6	0.03	3.5	36.2	
CSAL	Concord	Salvio Street	-122.03824	37.97569	57.110	2.9	0.02	3.0	36.1	
GVPR	Green Valley	Parish Rd	-122.11316	38.11413	140.446	1.0	0.4	1.0	8.3	
GVSR	Green Valley	S. Ridgefield Way	-122.13680	38.16584	117.287	3.4	0.6	3.2	5.8	
GVRT	Green Valley	Red Top Rd	-122.15054	38.19848	343.750	3.7	0.1	3.9	31.4	
GVDY	Green Valley	Dynasty Court	-122.15560	38.21861	175.568	0.7	0.5	0.8	5.8	
GVMR	Green Valley	Mason Rd	-122.16186	38.23603	143.137	2.6	0.3	1.9	10.8	
GVCL	Green Valley	Crystal Lake	-122.24806	38.47626	95.442	0.9	0.3	0.7	7.3	LR exclude '09,'12. Not read '15
HCHC	Hunting Creek	Hunting Creek	-122.38873	38.81388	179.400	2.2	0.5	2.7	7.1	Not read 2015
MSKP	Maacama	Skipstone Ranch	-122.82647	38.70320	111	1.6	0.3	1.7	7.2	
MAMR	Maacama	Middle Ridge	-123.05070	38.93464	144.300	2.9	0.7	3.4	7.1	
MUKI	Maacama	Sanford Ranch Rd	-123.16748	39.13906	288.753	4.2	0.1	4.2	22.1	
MWIL	Maacama	W. Commercial Ave	-123.35612	39.41242	124.869	5.4	0.1	5.2	23.7	
NLAR	West Napa	Las Amigas Rd	-122.31640	38.23422	76.05	—[3]	—	—		Afterslip of Aug 24, 2014 M6.0
NWIT	West Napa	Withers Rd	-122.32516	38.25157	138.95	—[3]	—	—		"
NHNR	West Napa	Henry Rd	-122.33650	38.27316	70.8	—[3]	—	—		"
NLOD	West Napa	Leaning Oak Dr	-122.34426	38.29809	64.720	—[3]	—	—		"
NELW	West Napa	Ellen Wy	-122.33782	38.30813	85	—	—	—		"
RCWC	Rodgers Creek	Wildcat Mountain	-122.47916	38.19870	109.680	0.3	0.5	0.3	5.6	
RCSM	Rodgers Creek	Sonoma Mtn. Rd	-122.59046	38.30928	137.926	1.8	0.2	1.7	12.7	
RCSD	Rodgers Creek	Solano Drive	-122.69446	38.43687	90.502	1.4	0.1	1.6	12.7	
RCFG	Rodgers Creek	Fountaingrove Blvd.	-122.71750	38.47995	76	—	—	--	--	Abandoned 2015
RCMW	Rodgers Creek	Mark West Springs Rd.	-122.73807	38.50169	152.000	4.4	0.7	5.0	7.4	
RCBR	Rodgers Creek	Brooks Road	-123.79490	38.57730	65.951	.-1.2	1.3	-1.5	4.5	Not read 2015
RCBP	Rodgers Creek	Bridle Path	-122.86539	38.64186	121.5	—	—	—	0.0	

*Average = total slip/total time

[1]Combined ESE and ESW lengths

[2]Number of years of observation

[3]Slip associated with M6.0 earthquake exhibits logarithmic decay over time, not linear (Lienkaemper and others, 2016)

Table 2. Average Rates of Right-Lateral Movement, Hayward Fault

Distance from Pt. Pinole (km)	Site:	Site Name	Longitude (WGS84)	Latitude (WGS84)	Length (m)	Linear regression average creep rate (mm/yr)	± (mm/yr)	Average* creep rate (mm/yr)	yr†	Note
4.49	HCCC	Contra Costa College	-122.33902	37.96918	142.58	5.2	0.1	5.0	35.1	**
8.37	HOLV	Olive Drive	-122.30959	37.94252	142.62	5.5	0.1	5.5	26.0	
10.83	HTBR	Thors Bay Road	-122.29294	37.92449	119.20	3.6	0.1	3.9	26.0	
14.05	HFLO	Florida Avenue	-122.27340	37.89980	126.11	2.7	0.04	2.7	18.1	1
17.82	HSTA	Memorial Stadium	-122.25061	37.87066	~161	4.8	0.03	4.8	48.8	
18.43	HDWT	Dwight Way	-122.24107	37.86447	132.35	5.1	0.2	5.0	18.1	
20.84	HTEM	Temescal	-122.23137	37.84853	153.92	4.3	0.1	4.2	41.5	
23.92	HLSA	LaSalle Ave	-122.21005	37.82638	182.84	4.2	0.1	4.6	22.6	
25.98	HLNC	Lincoln	-122.19863	37.80999	110.41	3.7	0.1	3.8	45.4	
27.81	H39A	39th	-122.18931	37.79504	137.81	4.4	0.1	4.1	41.4	
30.68	H73A	73rd	-122.16977	37.77426	89.81	3.4	0.1	3.4	22.4	
33.39	HENC	Encina Way	-122.15148	37.75453	123.80	2.5	0.1	3.3	26.1	
36.55	HCHB	Chabot Park	-122.12993	37.73184	170.05	4.0	0.1	4.0	22.3	
38.28	HFMT	Fairmont	-122.12131	37.71749	166.64	4.6	0.2	4.4	18.1	
41.11	H167	167th	-122.10578	37.69495	90.35	4.7	0.1	4.9	23.1	
43.22	HROS	Rose Street	-122.09121	37.67983	153.77	4.5	0.04	4.4	35.2	
44.56	HDST	D Street	-122.08162	37.67021	110.86	4.6	0.03	5.0	35.2	
45.64	HPAL	Palisade	-122.07397	37.66270	131.66	4.9	0.2	4.6	38.7	
47.72	HSEP	Sepulchre	-122.05902	37.64798	107.14	5.4	0.1	5.6	21.1	
50.15	HWDL	Woodland	-122.04140	37.63097	66.58	4.5	0.1	4.5	45.7	1
52.60	HCHM	Chimes	-122.02325	37.61422	118.65	6.3	0.1	5.9	21.1	
55.65	HAPP	Appian Way	-122.00193	37.59240	132±2	5.8	0.04	5.8	36.0	
59.09	HGIL	Gilbert	-121.98094	37.56645	89.26	5.7	0.1	5.8	32.0	2
62.25	HRKT	Rockett Drive	-121.96187	37.54210	103.23	5.4	0.1	5.4	36.0	
62.64	HHAN	Hancock	-121.95914	37.53942	88.51	6.4	0.2	6.0	33.7	2
63.10	HUNI	Union	-121.95584	37.53614	168.10	6.5	0.1	6.5	22.7	2
65.29	HPIN	Pine	-121.94181	37.51973	97.65	7.6	0.3	7.6	26.5	2
66.29	HCAM	Camellia Drive	-121.93528	37.51235	88.35	4.8	0.1	5.0	25.6	2
66.67	HPMD	Parkmeadow Drive	-121.93262	37.50960	156.91	6.4	0.1	6.1	23.5	2
67.02	HSGR	S. Grimmer	-121.93046	37.50720	129.54	5.8	0.2	6.1	33.2	2
67.21	HONO	Onondaga	-121.92894	37.50516	72.88	3.3	0.2	3.2	32.4	2,3,**
68.45	HMSS	Mission	-121.92182	37.49629	168.94	5.3	0.2	4.4	21.6	2,4,**
74.22	HCCD	Country Club Drive	-121.88548	37.45340	94.4	—	—	—	0.0	

1) Array may miss significant fault traces
2) Slip rate includes considerable slow-down following 1989 Loma Prieta Earthquake
3) Array misses a major creeping fault trace
4) Not read in 2013 due to construction
*Average = total slip/total time
**Estimated value using simple average for missing data
†Number of years observed
HSTA Stadium array rebuilt in Sept. 2012, needs new L (IS-ES) measurement

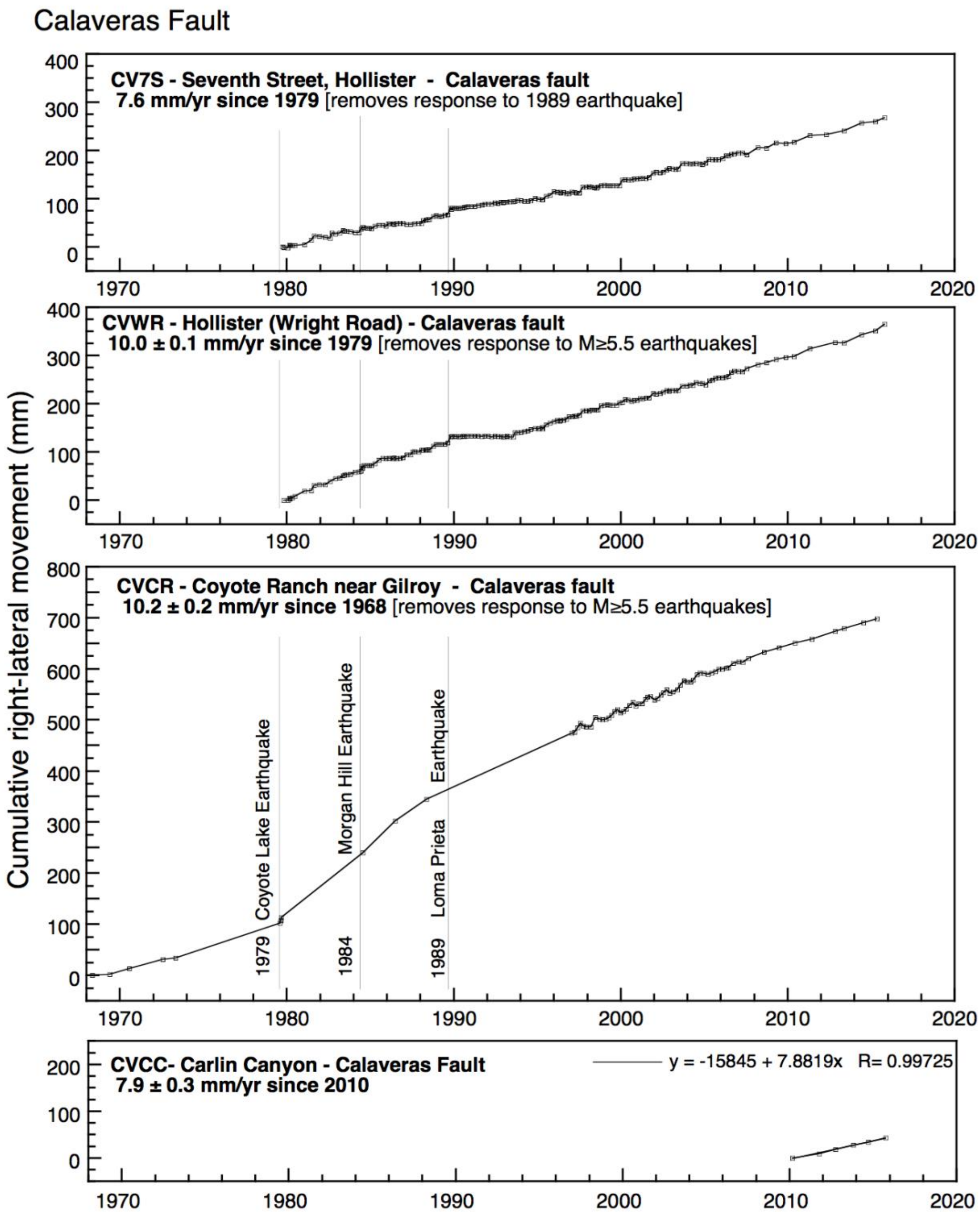

Figure 3. Alinement-array measurements, Calaveras Fault. Straight line through the data indicates linear regression fit to data given by associated equations y (creep, mm); x (time, yr); R, correlation coefficient. CV7S, CVWR and CVCR average rate derived by multiple linear regression to remove

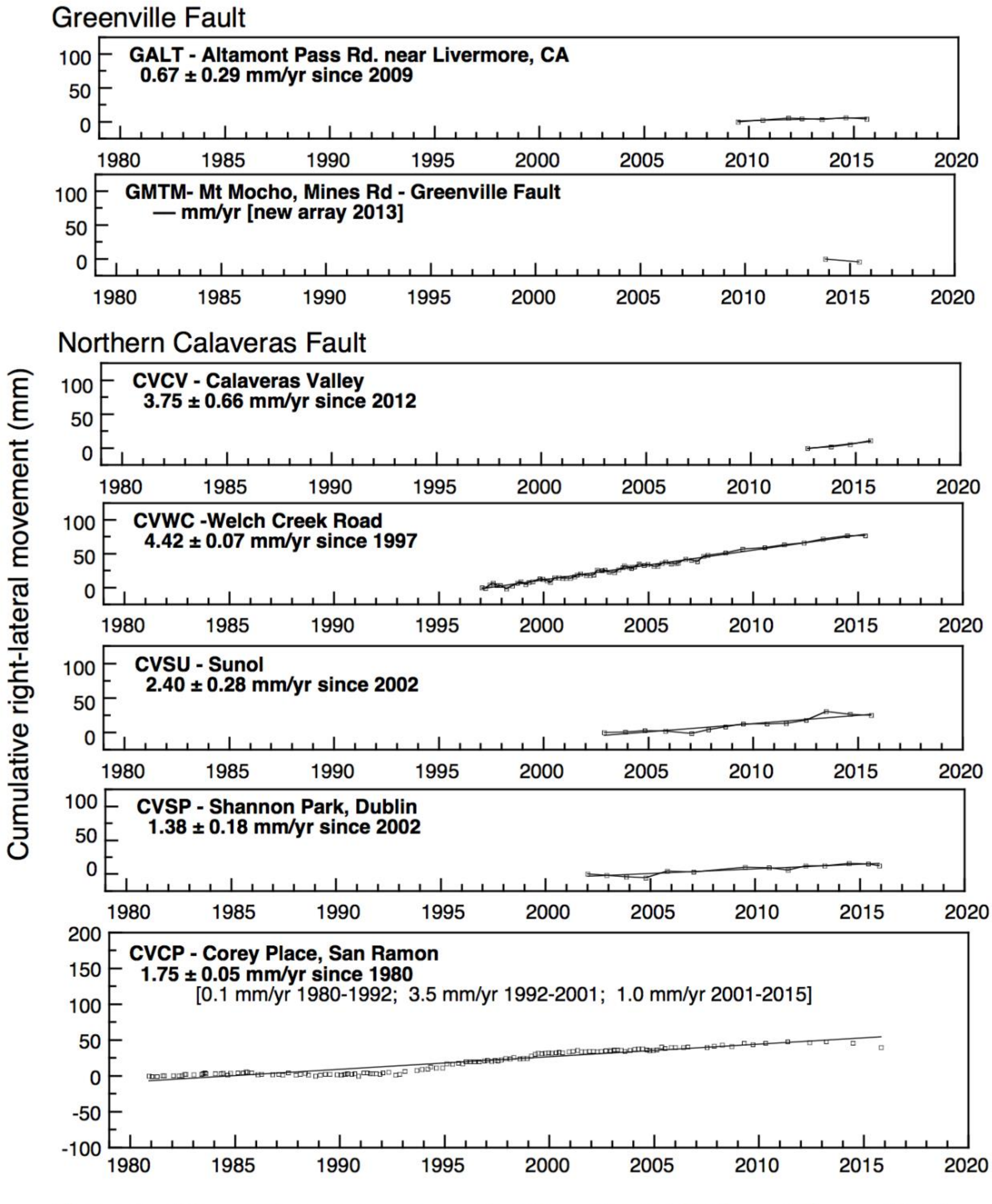

Figure 4. Alinement-array measurements, Greenville and Northern Calaveras Faults

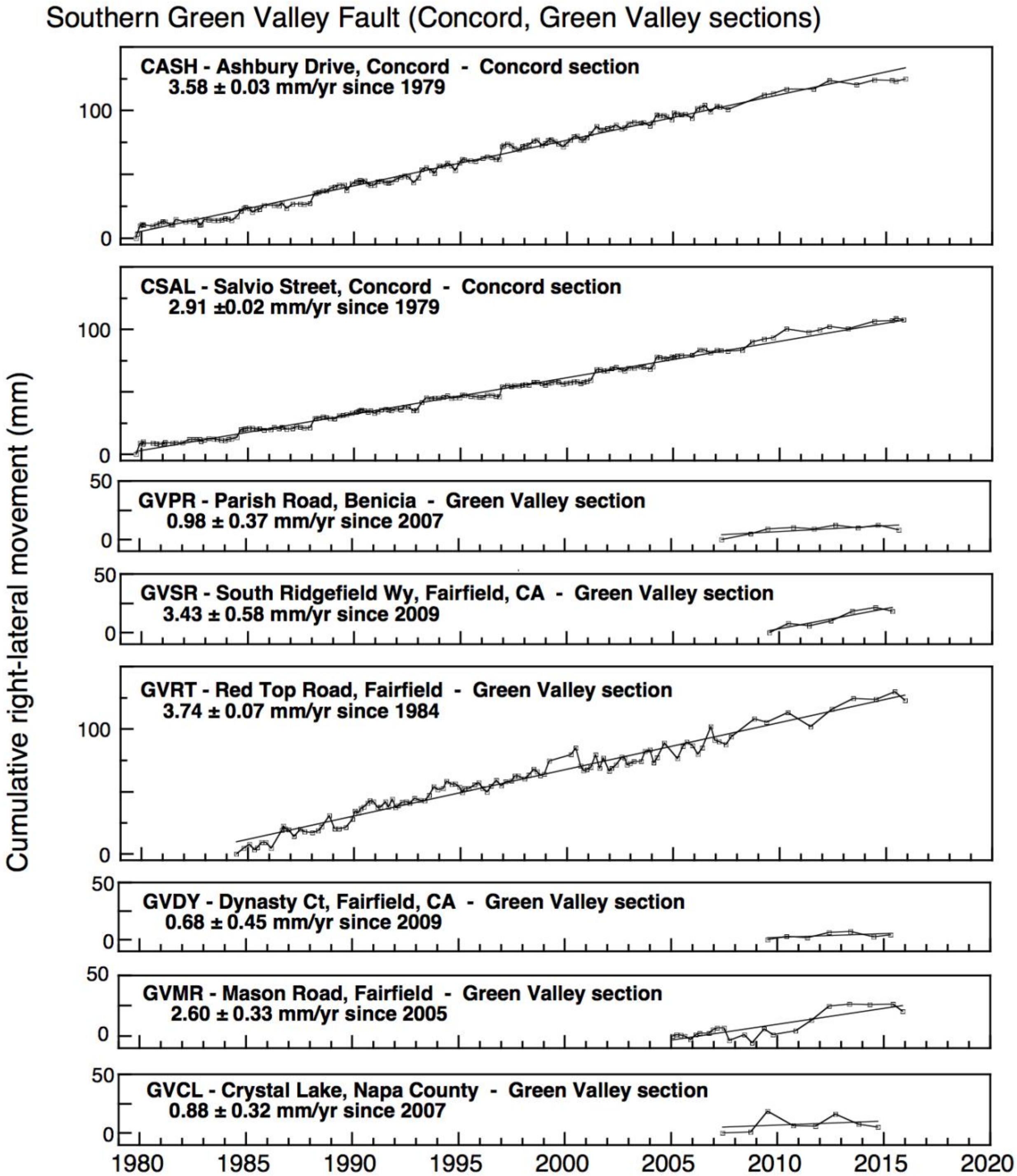

Figure 5a. Alinement array measurements, Southern Green Valley Fault.

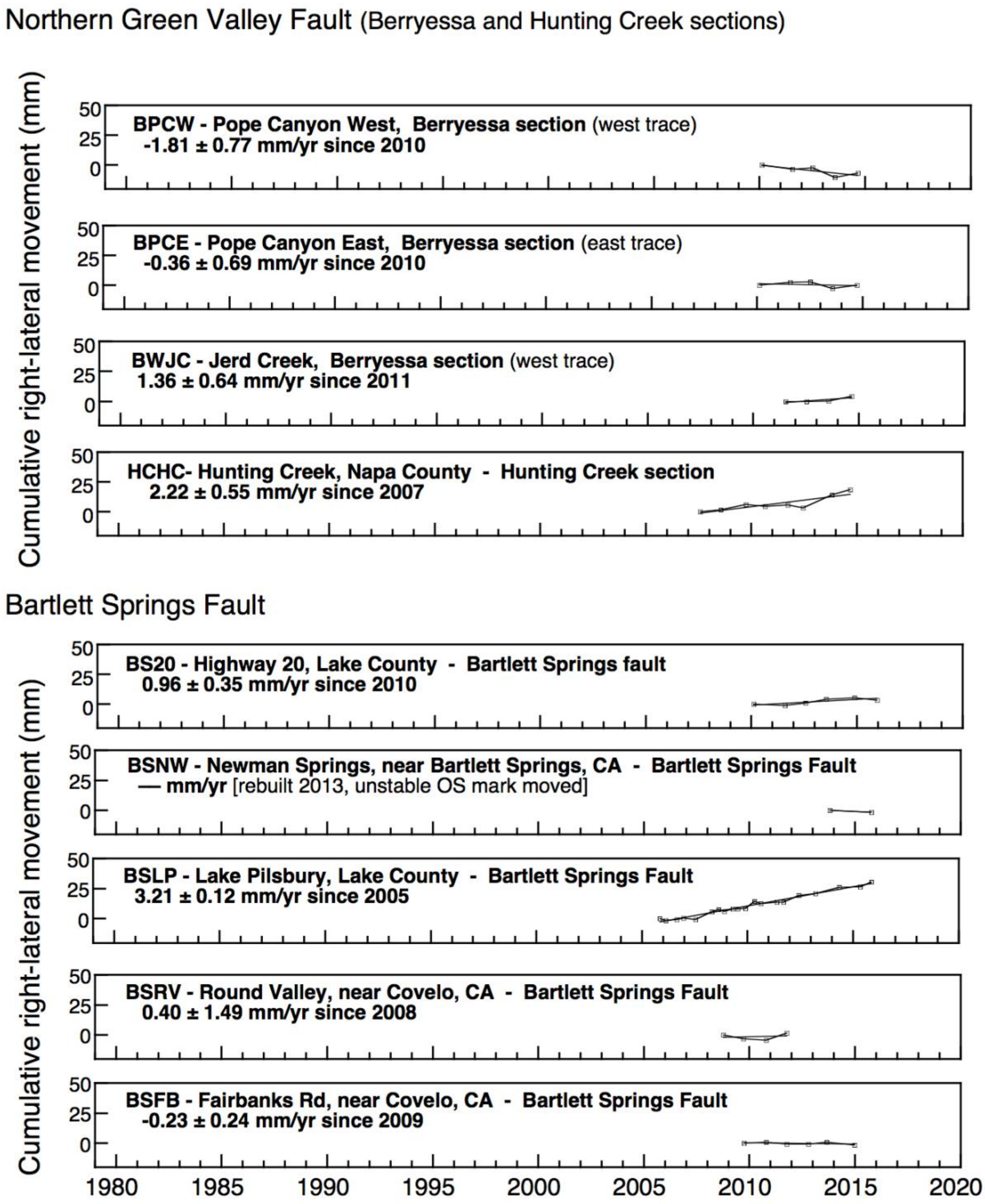

Figure 5b. Alinement array measurements, Northern Green Valley and Bartlett Springs Faults

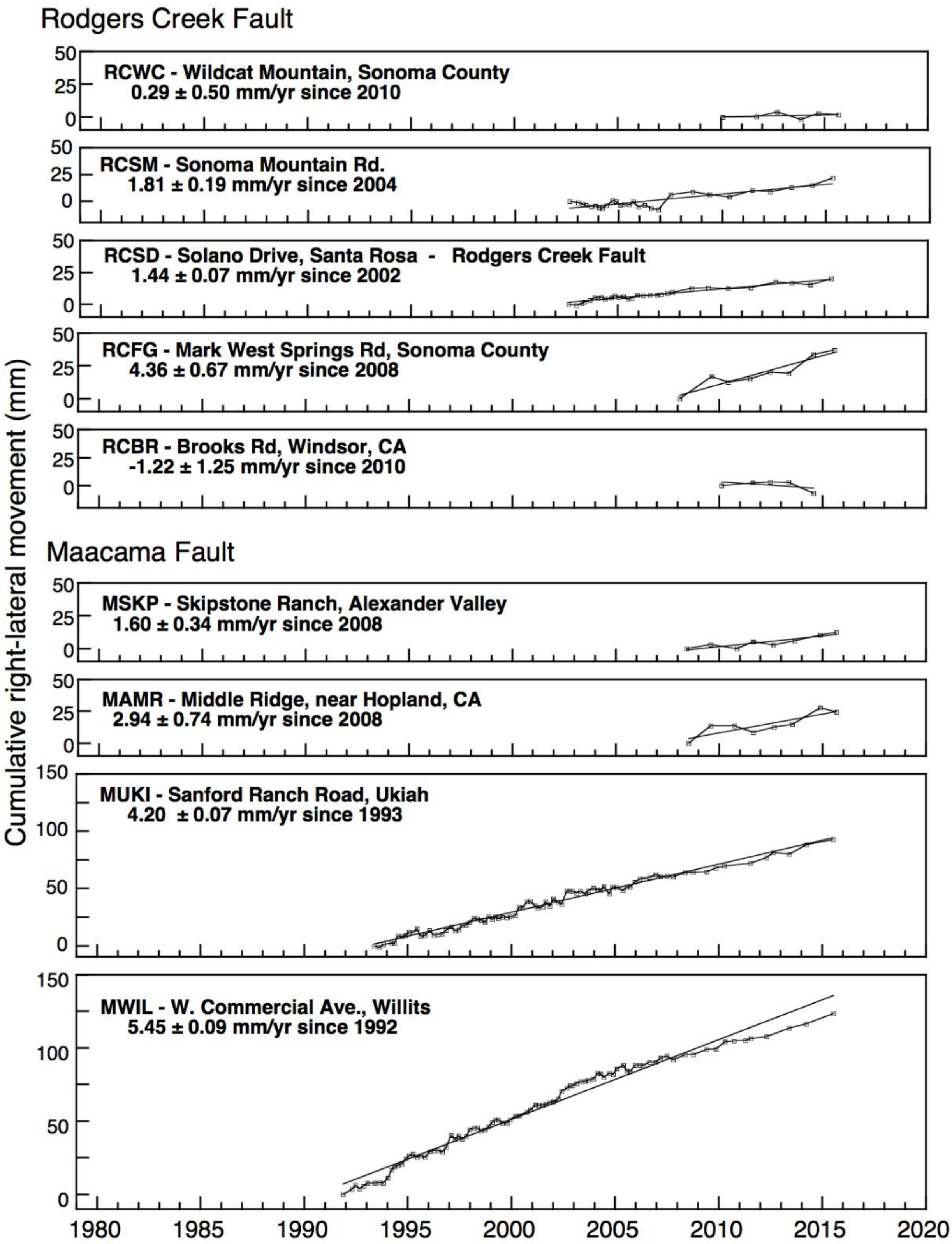

Figure 6. Alinement array measurements, Rodgers Creek and Maacama Faults.

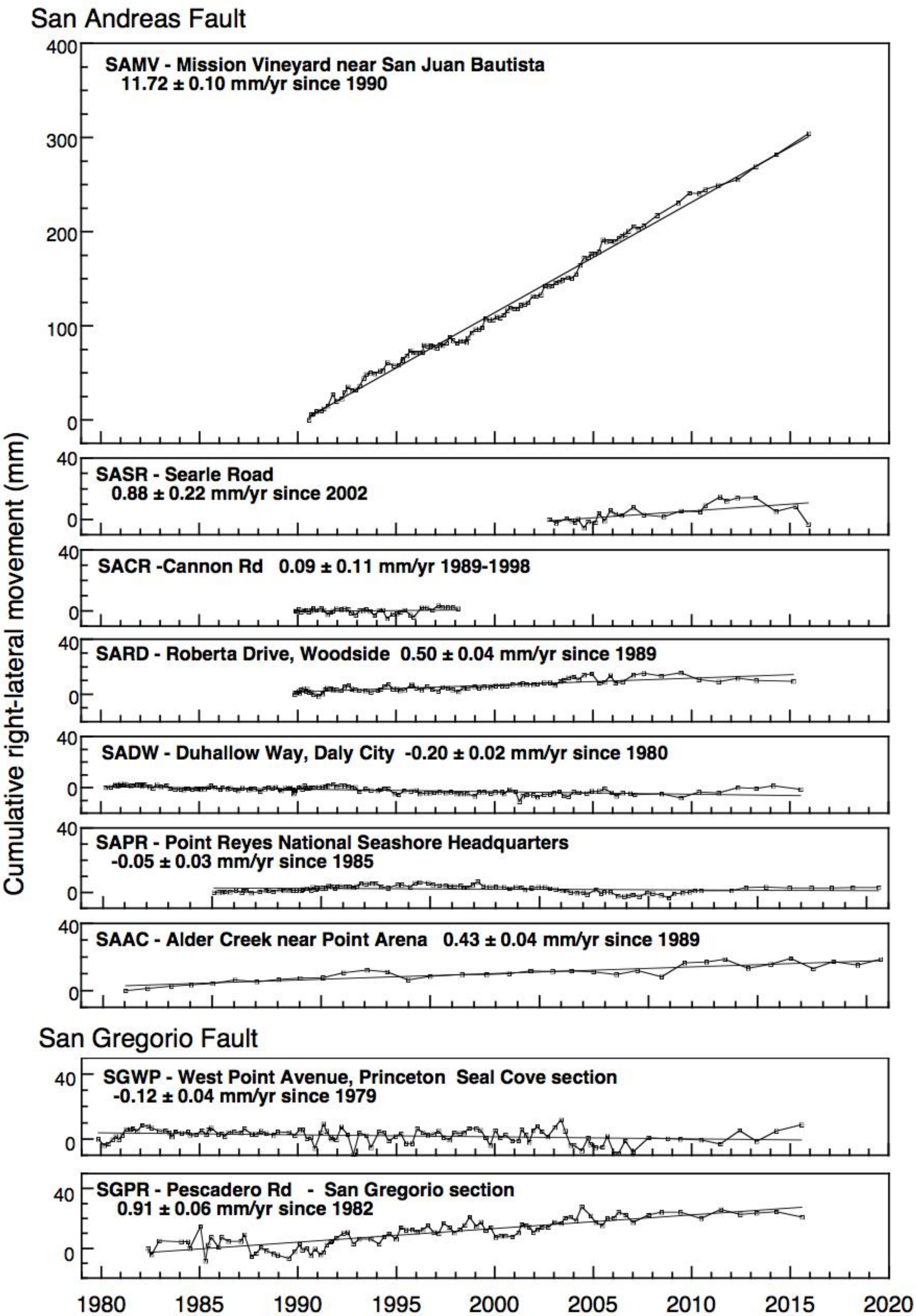

Figure 7. Alinement array measurements, San Andreas and San Gregorio faults.

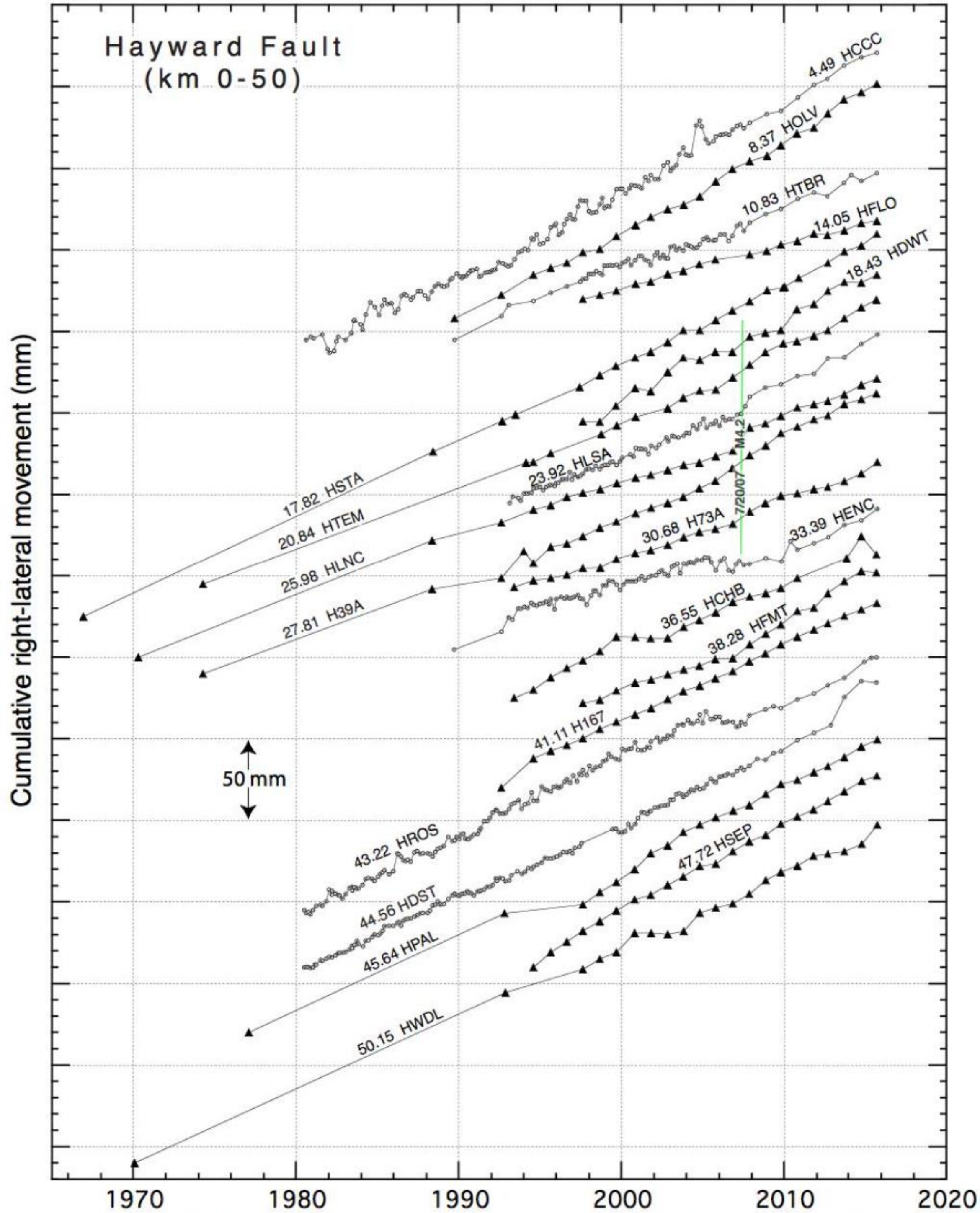

Figure 8. Alinement array measurements, Hayward Fault, sites from km 0 to 50, labeled by km distance (Table 2, Fig. 2).

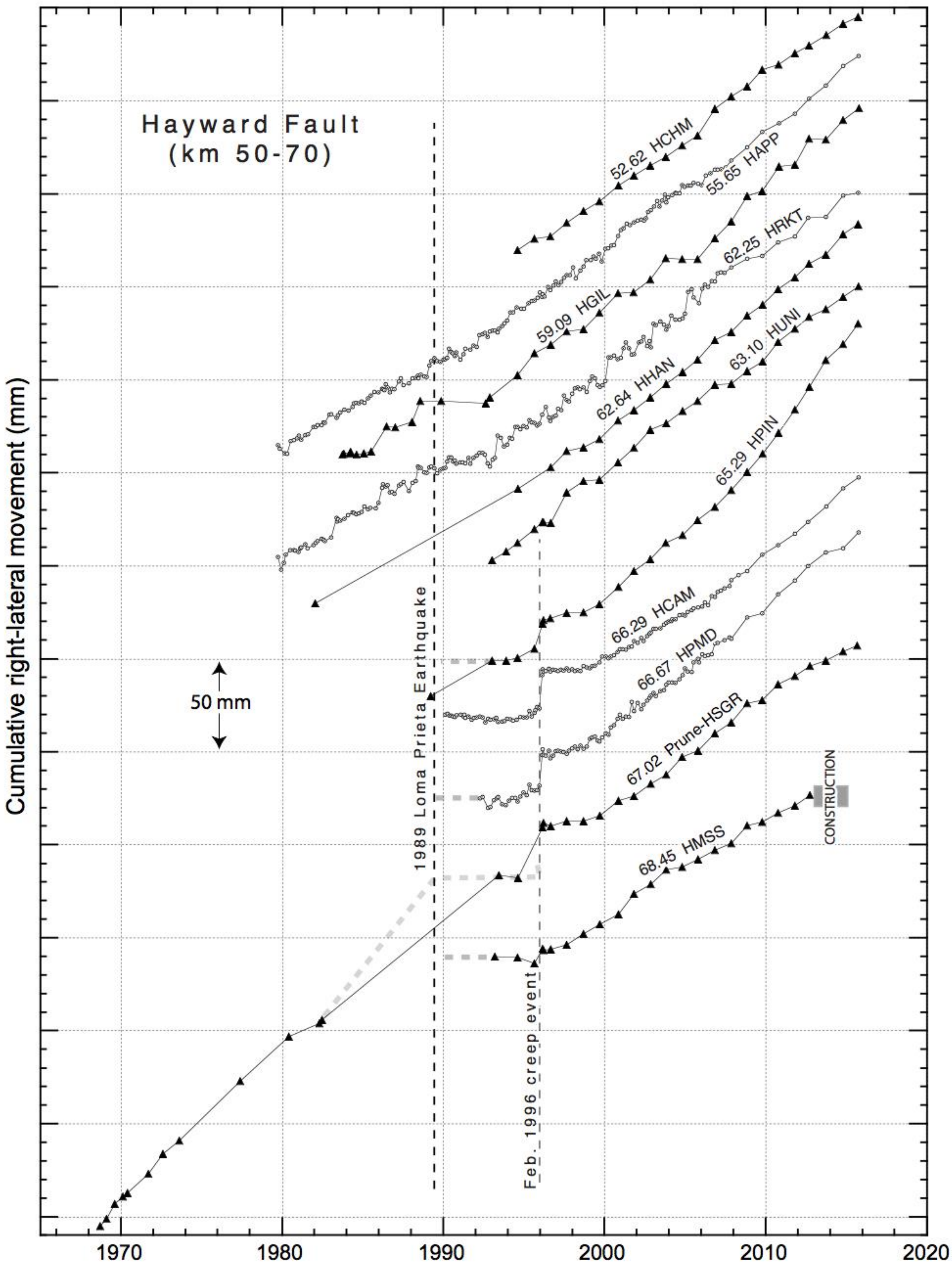

Figure 9. Alinement-array measurements Hayward Fault, sites from km 50 to 70.

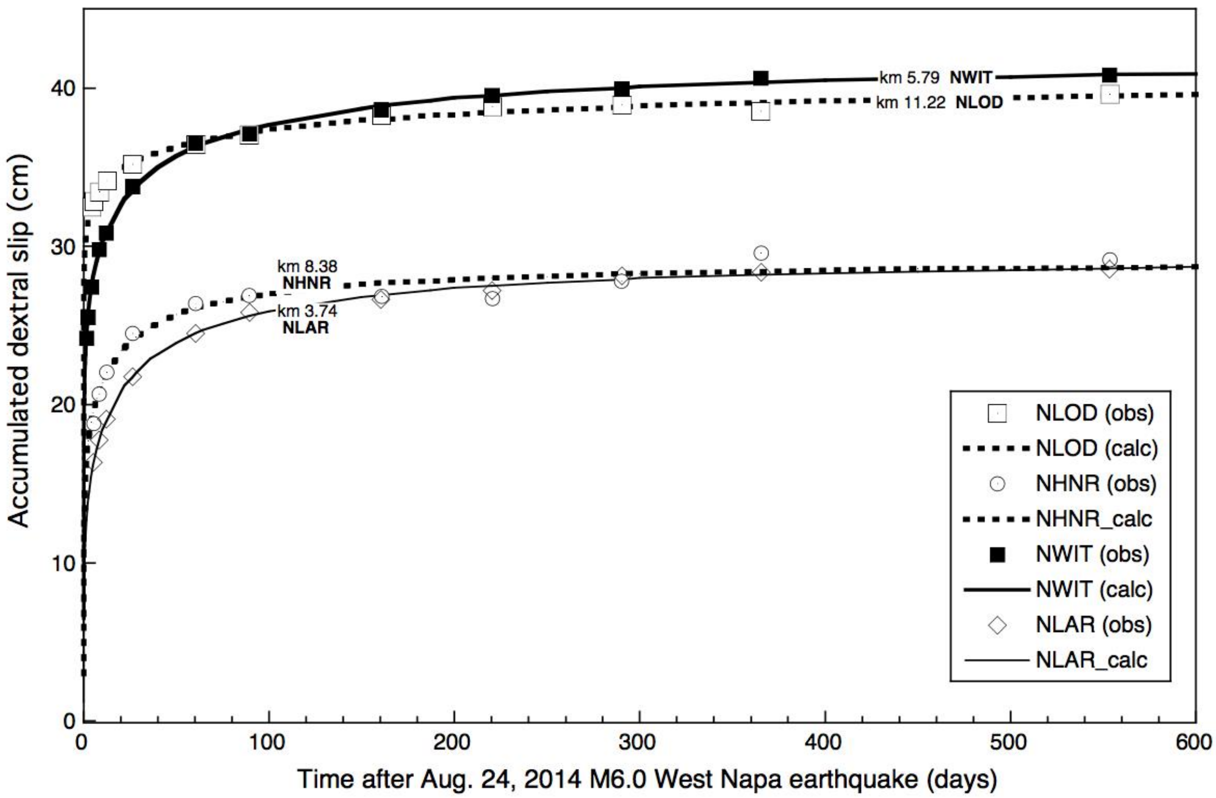

Figure 10. Alinement array observations across the West Napa Fault rupture associated with the Aug. 24, 2014 earthquake. Total slip based on adjacent offset cultural features. Calculated curves based on AFTER best fit (Boatwright and others, 1986). Array NELW on a branch fault had no afterslip. See Lienkaemper and others (2016).